

LAQGSM03.03 Upgrade and its Validation

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Abstract

This paper presents part of an internal LANL Progress Report on LAQGSM03.03, an upgrade of the Los Alamos version of the Quark-Gluon String Model event generator for MCNPX/6 and MARS15 transport codes and on its validation and testing against a large variety of recent measurements. We present here an analysis with LAQGSM03.03 of the recent PHENIX mid-rapidity spectra of π^+ , π^- , K^+ , K^- , p , and \bar{p} produced in ultra-relativistic $p + p$ interactions at $\sqrt{s} = 200$ GeV; GSI cross sections for the fragmentation of ^{208}Pb at 1 GeV/nucleon on ^9Be ; fragmentation cross sections of ^{28}Si on H, C, Al, Cu, Sn, and Pb at energies from 290 to 1200 MeV/nucleon measured recently at HIMAC and BNL; recent HIMAC data on B, Be, Li, and He production cross sections from fragmentation of ^{12}C on H, C, Al, Cu, Sn, and Pb at 290 and 400 MeV/nucleon; BNL data on fragmentation cross sections of ^{56}Fe on H, C, Al, Cu, and Pb targets at 1.05 GeV/nucleon; recent π^+ and π^- spectra from 6.4, 12.3, and 17.5 GeV/c $p + ^9\text{Be}$ from the E910 BNL measurements; and fragmentation cross sections of ^{40}Ca , ^{48}Ca , ^{58}Ni , and ^{64}Ni on ^9Be and ^{181}Ta at 140 MeV/nucleon, and of ^{86}Kr at 64 MeV/nucleon on the same targets measured recently at NSCL-MSU and RARF-RIKEN, respectively.

1. Introduction

During recent years, for a number of applications like Accelerator Transmutation of nuclear Wastes (ATW), Accelerator Production of Tritium (APT), Spallation Neutron Source (SNS), Rare Isotope Accelerator (RIA), Proton Radiography (PRAD) as a radiographic probe for the Advanced Hydro-test Facility, astrophysical work for NASA, and other projects, we have developed at the Los Alamos National Laboratory improved versions[1, 2] of the Cascade-Exciton Model (CEM) [3], to describe nucleon-, pion-, and photon-induced reactions at incident energies up to about 5 GeV and the Los Alamos version of the Quark-Gluon String Model (LAQGSM) [4, 5], to describe reactions induced by particles and nuclei at energies up to about 1 TeV/nucleon (see further references in [6]–[12]).

We present here the latest version of LAQGSM, LAQGSM03.03, which in comparison with its predecessors, is developed to describe better nuclear reactions at very high energies (above 20 GeV/nucleon), and which uses, for consistency, the preequilibrium, evaporation, fission, and Fermi break-up models in exactly the same form as developed previously for the latest version of our low-energy event generator CEM03.02 [12]; no longer produces the light unstable final

products ${}^6\text{B}$, ${}^6\text{Be}$, ${}^5\text{Li}$ ${}^6\text{H}$, or ${}^5\text{H}$, that could be produced in the previous versions of LAQGSM in very rare cases via some very asymmetric fission events (compare the results shown in Tabs. 1 and 2 of Ref. [13]): LAQGSM03.03 causes such unstable products to disintegrate via Fermi breakup independently of their excitation energy. Finally, some bugs and small errors observed in previous versions of LAQGSM are fixed; many useful comments are added.

2. LAQGSM03.03 Upgrade

The code LAQGSM03.03 described here is the latest modification of LAQGSM [4], which in its turn is an improvement of the Quark-Gluon String Model (QGSM) [14]. It describes reactions induced by both particles and nuclei, as a three-stage process: Intra-Nuclear Cascade (INC), followed by preequilibrium emission of particles during the equilibration of the excited residual nuclei formed after the INC, followed by evaporation of particles from compound nuclei or fission. When the cascade stage of a reaction is completed, we use the coalescence model described in Refs. [15, 16] to “create” high-energy d , t , ${}^3\text{He}$, and ${}^4\text{He}$ by final state interactions among emitted cascade nucleons, already outside of the target and projectile nuclei. If the excited compound nucleus produced after the preequilibrium stage of a reaction is heavy enough ($Z \geq 65$), it may fission, with subsequent evaporation of particles from the fission fragments. Such processes are described by LAQGSM03.03 using an improved and updated version of the Generalized Evaporation/fission Model (GEM2) by Furihata [17]. On the other hand, if the excited nucleus produced after the fast INC stage of a reaction, during emission of particles at the preequilibrium or evaporation stages of reaction, or if the fission fragment produced via a very asymmetric fission becomes quite light ($A < 13$) LAQGSM03.03 describes its further cooling and disintegration using the Fermi break-up model, based on the seminal ideas of Bohr and Fermi [18], instead of using the preequilibrium and evaporation models. An illustrative scheme of nuclear reaction calculations by LAQGSM03.03 is shown in Fig. 1.

Striving to make the predictive power of LAQGSM as high as possible, we have revised, updated, and improved the nuclear reaction models used in our event generator. A brief listing of the physics and of the major recent improvements in LAQGSM follows.

INC

The first and fastest stage of reactions is described by LAQGSM with a recently improved version [5, 10] of the time-dependent intra-nuclear cascade model developed initially at JINR in Dubna, often referred to in the literature as the Dubna intra-nuclear Cascade Model, DCM (see [15] and references therein). The DCM models interactions of fast cascade particles (“participants”) with nucleon spectators of both the target and projectile nuclei and includes as well interactions of two participants (cascade particles). It uses experimental cross sections (or those calculated by the Quark-Gluon String Model [14, 19, 20, 21] for energies above 4.5 GeV/nucleon) for these elementary interactions to simulate angular and energy distributions of cascade particles, and also considers the Pauli exclusion principle. In contrast to the earlier versions [22, 23] of the INC developed at Dubna and utilized with our recent revision and improvement in CEM03.01 [2], DCM uses a continuous nuclear density distribution (instead of the approximation of several concentric zones, where inside each the nuclear density is considered to be constant); therefore, it does not need to consider refraction and reflection of cascade

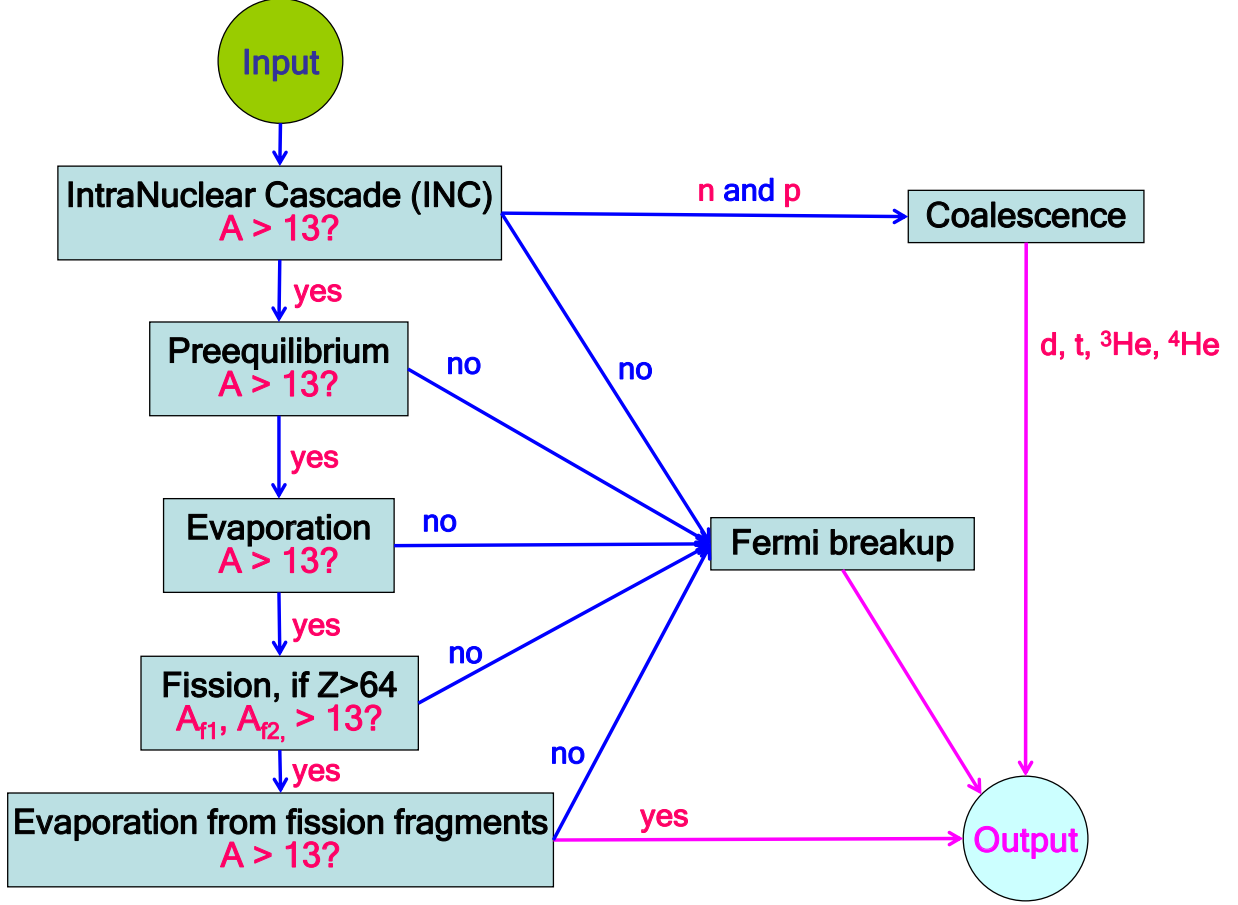


Figure 1: General scheme of nuclear reaction calculations by LAQGSM03.03.

particles inside or on the border of a nucleus; it also keeps track of the time of an intra-nuclear collision and of the depletion of the nuclear density during the development of the cascade (the so-called “trawling effect”).

Recently, we developed [10] new approximations to describe more accurately experimental elementary energy and angular distributions of secondary particles from hadron-hadron and photon-hadron interactions using available data and approximations published by other authors. The condition for transition from the INC stage of a reaction to preequilibrium was changed; on the whole, the INC stage in LAQGSM03.03 is longer while the preequilibrium stage is shorter in comparison with earlier versions. A new, high-energy photonuclear reaction model was developed and incorporated [5] into the INC of LAQGSM, that allows us to calculate reactions induced by photons of up to tens of GeV energy. The algorithms of many INC routines were changed and some INC routines were rewritten, which speeded up the code significantly; some preexisting bugs in the DCM were fixed; many useful comments were added.

Specifically for LAQGSM03.03 we have modified our INC for a better description of nuclear reactions at very high energies (above 20 GeV/nucleon), namely:

1) We have incorporated into LAQGSM the latest fits to currently available evaluated experimental database for the total and elastic π^+p , π^-p , pp , and pn cross sections (see Chapter 40 in the last Review of Particle Physics [24] and references therein). We use in LAQGSM03.03 these approximations at energies above 20–30 GeV, and our own approximations developed for CEM03.01 [2] at lower energies.

2) Previously, we have used LAQGSM only at energies below 800 GeV. We studied recently the possibility of using LAQGSM03.03 at ultra-relativistic energies, above 1 TeV. Our results show that to describe ultra-high energy reactions, the value of the parameter $\sigma_\perp = 0.51$ GeV/c in the transverse momentum distribution of the constituent quarks of QGSM (see Eq. (12) in [4] or Eq. (10) in the first paper of Ref. [20]) has to be increased. As shown in Fig. 2, to describe properly $p + p$ interactions at $\sqrt{s} = 200$ GeV, which corresponds to $T_p \simeq 21314$ GeV, we need to use $\sigma_\perp = 2.0$ GeV/c. In other words, to be able to describe well with LAQGSM reactions induced by intermediate and high energy projectiles as well as reactions induced by ultra-relativistic energy projectiles, we need to use an energy dependent average transverse momentum parameter σ_\perp increasing with the projectile energy from 0.51 GeV/c at $T_p \leq 200$ GeV [4] to $\sigma_\perp \simeq 2$ GeV/c at $T_p \simeq 21$ TeV.

Preequilibrium (PREC)

LAQGSM03.03 uses the latest version of the Modified Exciton Model (MEM) [26] as implemented into the latest Cascade-Exciton Model code CEM03.02 [12] (and in the publicly available from RSICC version CEM03.01 [2]) to describe the relaxation of the nuclear excitation of nuclei produced in a reaction after the INC. MEM takes into account all possible nuclear transitions changing the number of excitons n with $\Delta n = +2, -2$, and 0, and considers all possible multiple subsequent emissions of n , p , d , t , ^3He , and ^4He . It assumes an equidistant-level scheme with the single-particle density g and takes into account corrections for the exclusion principle and indistinguishability of identical excitons. By neglecting the difference of matrix elements with different Δn , $M_+ = M_- = M_0 = M$, MEM estimates the value of M for a given nuclear state by associating the $\Delta n = +2$ transition with the probability for a quasi-free scattering of a nucleon above the Fermi level on a nucleon of the target nucleus, using systematics of available experimental nucleon-nucleon cross sections.

The condition for transition from the preequilibrium stage of a reaction to evaporation/fission is changed in comparison with the initial version of CEM [3]; on the whole, the preequilibrium stage in LAQGSM03.03 is shorter while the evaporation stage is longer in comparison with earlier versions. The widths for complex-particle emission are changed by fitting the probability γ_β of several excitons to “coalesce” into a complex particle that may be emitted during the preequilibrium stage (see details in [2, 3]) to available experimental data on reactions induced by protons and neutrons. We have incorporated into CEM03.01 the Kalbach systematics [27] to describe angular distributions of both preequilibrium nucleons and complex particles at incident energies up to 210 MeV. At higher energies, we use our own CEM approach (based on Eqs. (32,33) of Ref. [2]). Algorithms of many PREC routines are changed and almost all PREC routines are rewritten, which has speeded up the code significantly. Finally, some bugs are fixed.

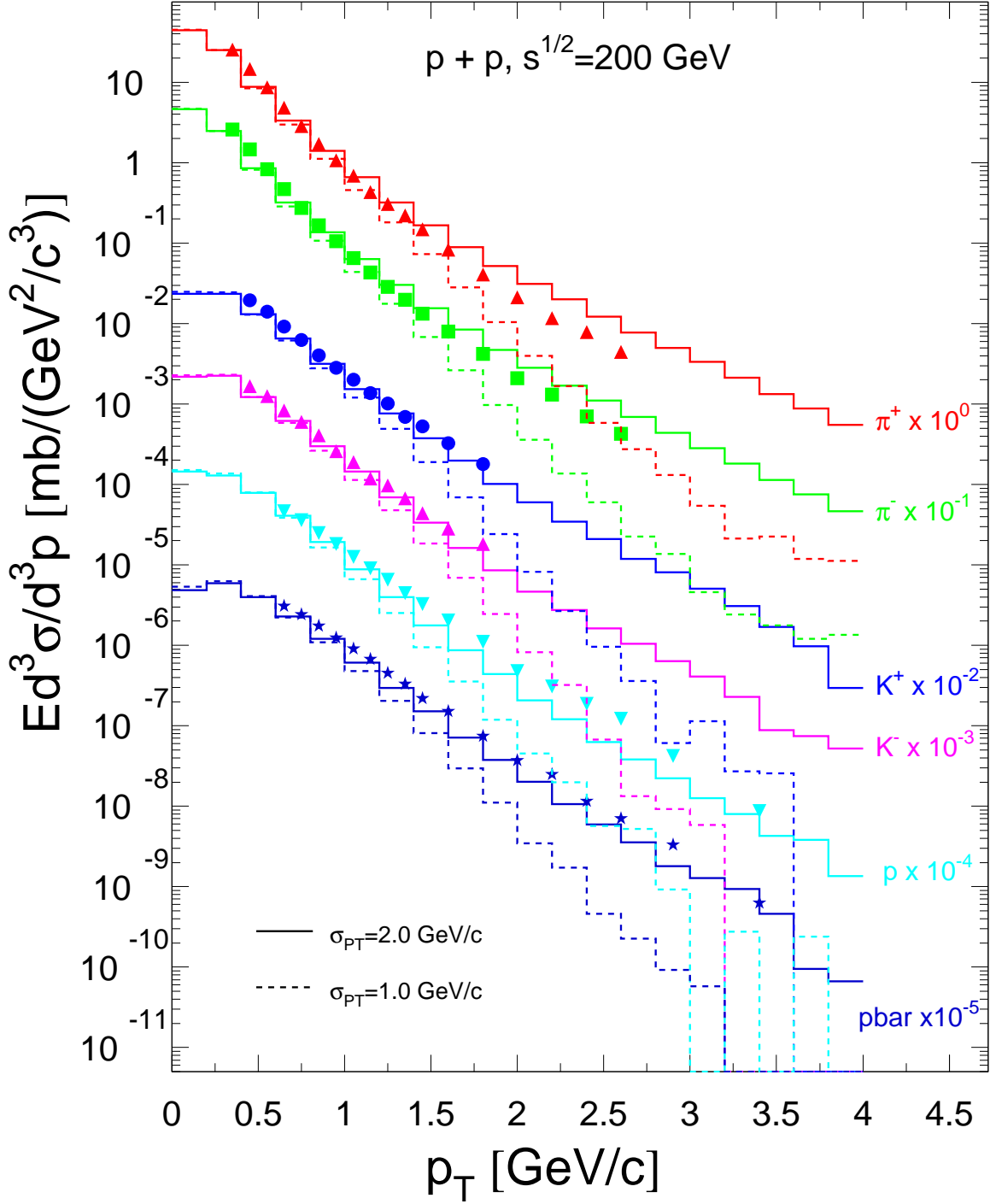


Figure 2:

Mid-rapidity spectra of π^+ , π^- , K^+ , K^- , p , and \bar{p} produced in ultra-relativistic $p + p$ interactions at $\sqrt{s} = 200$ GeV ($T_p = 21314$ GeV) calculated with values of the parameter $\sigma_{\perp} = 2.0$ GeV/c (solid histograms) and $\sigma_{\perp} = 1.0$ GeV/c (dashed histograms) in the transverse momentum distribution of the constituent quarks of the QGSM compared with recent RHIC data [25]

Evaporation

LAQGSM03.03 uses an extension of the Generalized Evaporation Model (GEM) code GEM2 by Furihata [17] after the preequilibrium stage of reactions to describe evaporation of nucleons, complex particles, and light fragments heavier than ^4He (up to ^{28}Mg) from excited compound nuclei and to describe their fission, if the compound nuclei are heavy enough to fission ($Z \geq 65$). GEM describes evaporation with an extension by Furihata of the Dostrovsky evaporation model [28], to include up to 66 types of particles and light fragments that can be evaporated from an excited compound nucleus. A very detailed description of GEM2 together with a large amount of results obtained for many reactions using GEM2 coupled either with the Bertini INC or with ISABEL may be found in [17]; many useful details are presented in [2].

Fission

The fission model used in GEM2 is based on the model by Atchison [31], often referred in the literature as the Rutherford Appleton Laboratory (RAL) fission model, which is where Atchison developed it. The Atchison fission model was designed to describe only fission of nuclei with $Z \geq 70$. It assumes that fission competes only with neutron emission, *i.e.*, from the widths Γ_j of n, p, d, t, ^3He , and ^4He emission, the RAL code calculates the probability of evaporation of these particles. When a charged particle is selected to be evaporated, no fission competition is taken into account. When a neutron is selected to be evaporated, the code does not actually simulate its evaporation, instead it considers that fission may compete, and chooses either fission or evaporation of a neutron according to the fission probability P_f . This quantity is treated by the RAL code differently for elements above and below $Z = 89$. The mass, charge, and kinetic-energy distributions of fission fragments are described by RAL using semi-empirical systematics developed by Atchison based on experimental data available to him at that time.

Furihata used later, more extensive experimental data and made many changes in the calculation of both the fission widths and mass, charge, and kinetic-energy distributions of the fission fragments. Details are given in [2, 17]. In comparison with the original GEM2, the calculation of fission widths in LAQGSM03.03 is changed by fitting the ratio of the level-density parameters at the saddle point to those in the evaporation channel to the systematics of proton-induced fission cross sections by Prokofiev [29] (see details in [30]). This affects as well the relative probabilities of particle evaporation, in the case of heavy nuclei, where competition between evaporation and fission is considered.

In our codes, we have fixed first several observed uncertainties and small errors in the 2002 version of GEM2 which Dr. Furihata kindly sent us. We extend GEM2 to describe fission of lighter nuclei, down to $Z \geq 65$, and modify it [30] so that it provides a good description of fission cross sections when it is used after our INC and preequilibrium models. Several GEM2 routines are slightly modified in CEM03.01 and LAQGSM03.03 and some bugs are fixed.

Coalescence

The coalescence model implemented in LAQGSM03.03 is described in Refs. [15, 16]. In contrast to most other coalescence models for heavy-ion induced reactions, where complex particle spectra are estimated simply by convolving the measured or calculated inclusive spectra of nucleons with corresponding fitted coefficients (see, *e.g.*, [32] and references therein), LAQGSM03.03 uses in its simulations of complex particle coalescence real information about all emitted cascade nucleons and does not use convolutions of nucleon spectra. LAQGSM03.03 assumes that nucleons emitted during the INC stage of a reaction may form an appropriate composite particle, if they have a correct isotopic content and the differences in their momenta are smaller than p_c , equal to 90, 108, and 115 MeV/c for d , $t(^3\text{He})$, and ^4He , respectively. When, for example, an INC proton coalescences with an INC neutron into a deuteron, both of them are removed from the status of nucleons, leaving in the final state only the deuteron.

In comparison with the initial version [15, 16], in LAQGSM03.03 we have changed/deleted several routines and have tested them against a large variety of measured data on nucleon- and nucleus-induced reactions at different incident energies.

Fermi Breakup

The Fermi breakup model [18] describes a break-up of an excited nucleus into n components in the final state (*e.g.*, a possible residual nucleus, nucleons, deuterons, tritons, alphas, *etc.*) according to the n -body phase space distribution. The version of the Fermi breakup model code used in LAQGSM03.03 was developed in the former group of Prof. Barashenkov at the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The angular distribution of n emitted fragments is assumed to be isotropic in the c.m. system of the disintegrating nucleus and their kinetic energies are calculated from momentum-energy conservation. The Monte-Carlo method is used to randomly select the decay channel according to the corresponding probabilities. Then, for a given channel, LAQGSM03.03 calculates kinematic quantities for each fragment according to the n -body phase space distribution using the Kopylov method [33]. Generally, LAQGSM03.03 considers formation of fragments only in their ground and those low-lying states which are stable for nucleon emission. All formulas and algorithms used in the initial version are described in details by Amelin [34] and may be found in a shorter form in Ref. [2] as well, therefore we do not repeat them here.

In comparison with its initial versions, we have modified LAQGSM03.03 to decay some unstable light fragments that were produced by the original Fermi-breakup-model code described in [34]. As mentioned above, the initial routines that describe the Fermi breakup model were written more than twenty years ago in the group of Prof. Barashenkov at JINR, Dubna, and unfortunately had some problems. First, these routines allowed in rare cases production of some light unstable fragments like ^5He , ^5Li , ^8Be , ^9B , *etc.*, as a result of a break-up of some light excited nuclei. Second, they very rarely allowed even production of “neutron stars” (or “proton stars”), *i.e.*, residual “nuclei” produced via Fermi breakup that consist of only neutrons (or only protons). Lastly, these routines could even crash the code, due to cases of division by 0.

All these problems of the Fermi breakup model routines were addressed and solved by Dick Prael for CEM03.02 [12]; the changes were then put in LAQGSM03.02 [12]. Several bugs are also fixed.

However, even after solving these problems and after implementing the improved Fermi breakup model into CEM03.02 and LAQGSM03.02 [12], these event generators still could produce some unstable products via very asymmetric fission, when the excitation energies of those fragments were below 3 MeV so they were not checked and disintegrated with the Fermi breakup model. Table 1 in Ref. [13] shows an example of such results from an output of the reaction 1 GeV/nucleon $^{208}\text{Pb} + ^9\text{Be}$ calculated with LAQGSM03.02 [12]. We can see that from a total of 10^7 simulated inelastic events, LAQGSM03.02 produced 60 unstable light fragments, namely: one ^5H , twenty-three ^6H , one ^5Li , thirty ^6Be , one ^{13}Be , and four ^6B . The summed yield of all these unstable products is less than 0.0006% of the total yield of all products, so that production of these unstable nuclides affects by less than 0.0006% the other correct cross sections from this test problem. However, these unstable nuclides are non-physical and should be eliminated. This is the reason we have incorporated into LAQGSM03.03 a universal checking of all unstable light products. We force such unstable products to disintegrate via Fermi breakup independently of their excitation energy. Table 2 of Ref. [13] presents results for the same reaction as shown in Tab. 1 of that paper, but calculated with LAQGSM03.03. We can see that this version does not produce any such unstable light products.

3. Validation of LAQGSM03.03

We have tested the LAQGSM03.03 code against a large variety of particle-particle, particle-nucleus, and nucleus-nucleus reactions at energies from ~ 10 MeV/nucleon to ~ 1 TeV/nucleon, some measured very recently, and some earlier ones analyzed already with previous versions of this event generator. The general agreement of our results with the new experimental data is about the same as the agreement with the older data analyzed with previous versions of LAQGSM and published in Refs. [1], [4]–[12], [35]. Therefore, we present only comparisons of model results compared to several very recent measurements. We note that LAQGSM03.03 is being (or already has been) incorporated as the major event generator into the FNAL MARS15 [36] and LANL MCNP6 [37] and MCNPX [38] transport codes.

Figs. 3 and 4 show comparisons of recent GSI measurements [39] of the fragmentation of ^{208}Pb on ^9Be at 1 GeV/nucleon with results from LAQGSM03.03 and from its previous version, LAQGSM03.02 [12] (the same reaction and calculations as shown in Tabs. 1 and 2 of Ref. [13] discussed above). These GSI measurements were done with a special interest in heavy neutron-rich nuclei approaching the stellar nucleosynthesis r -process path around $A = 195$; they therefore contain experimental data only for products from Yb to Bi, while we calculate with our codes all possible products and present in Fig. 4 our predictions for yields of yet unmeasured nuclear products lighter than Yb. LAQGSM03.03 describes these new GSI data reasonably well and certainly no worse than its predecessor, also not predicting unstable non-physical light fragments, as did LAQGSM03.02.

Fig. 5 presents part of the recent extensive experimental data on fragmentation cross sections of ^{28}Si on H, C, Al, Cu, Sn, and Pb at energies from 290 to 1200 MeV/nucleon [40]. Such measurements are needed for NASA to plan long-duration spaceflights and to test the models

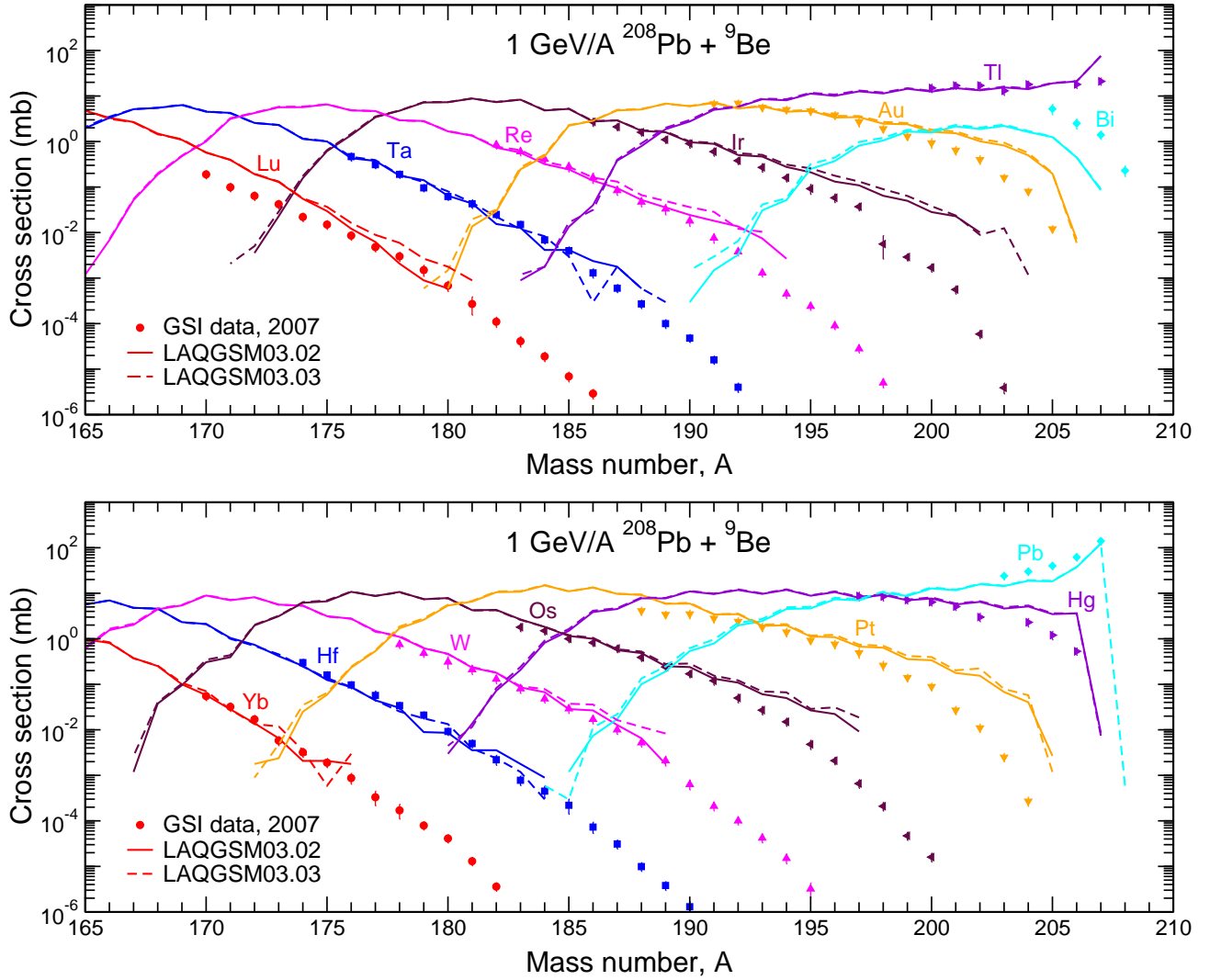


Figure 3: Mass-number distribution of the cross section for the production of thirteen elements from Yb to Bi from the reaction $1 \text{ GeV/nucleon } ^{208}\text{Pb} + ^9\text{Be}$. Symbols are GSI measurements of Nieto *et al.* [38]; dashed lines are results from LAQGSM03.03, while solid lines are results from LAQGSM03.02 [12].

used to evaluate radiation exposure in flight, and were performed at many incident energies in this energy range at the Heavy Ion Medical Accelerator in Chiba (HIMAC) and at Brookhaven National Laboratory (see details in [40] and references therein). We calculate in our model practically all these data, but here limit ourselves to examples of results for only three energies, for each measured target. For comparison, we present in Fig. 5 results from both LAQGSM03.03 (solid lines) and its predecessor LAQGSM03.02 (dashed lines). In general, LAQGSM03.03 describes these new data slightly better than LAQGSM03.02 [12], although this is not obvious on the scale of the figure. The agreement of our calculations with these data is excellent, especially considering that the results presented in this figure, just as all our other results, are obtained without fitting any parameters in the code; we simply input A and Z of the projectile and target and the energy of the projectile, then calculate without changing or fitting anything.

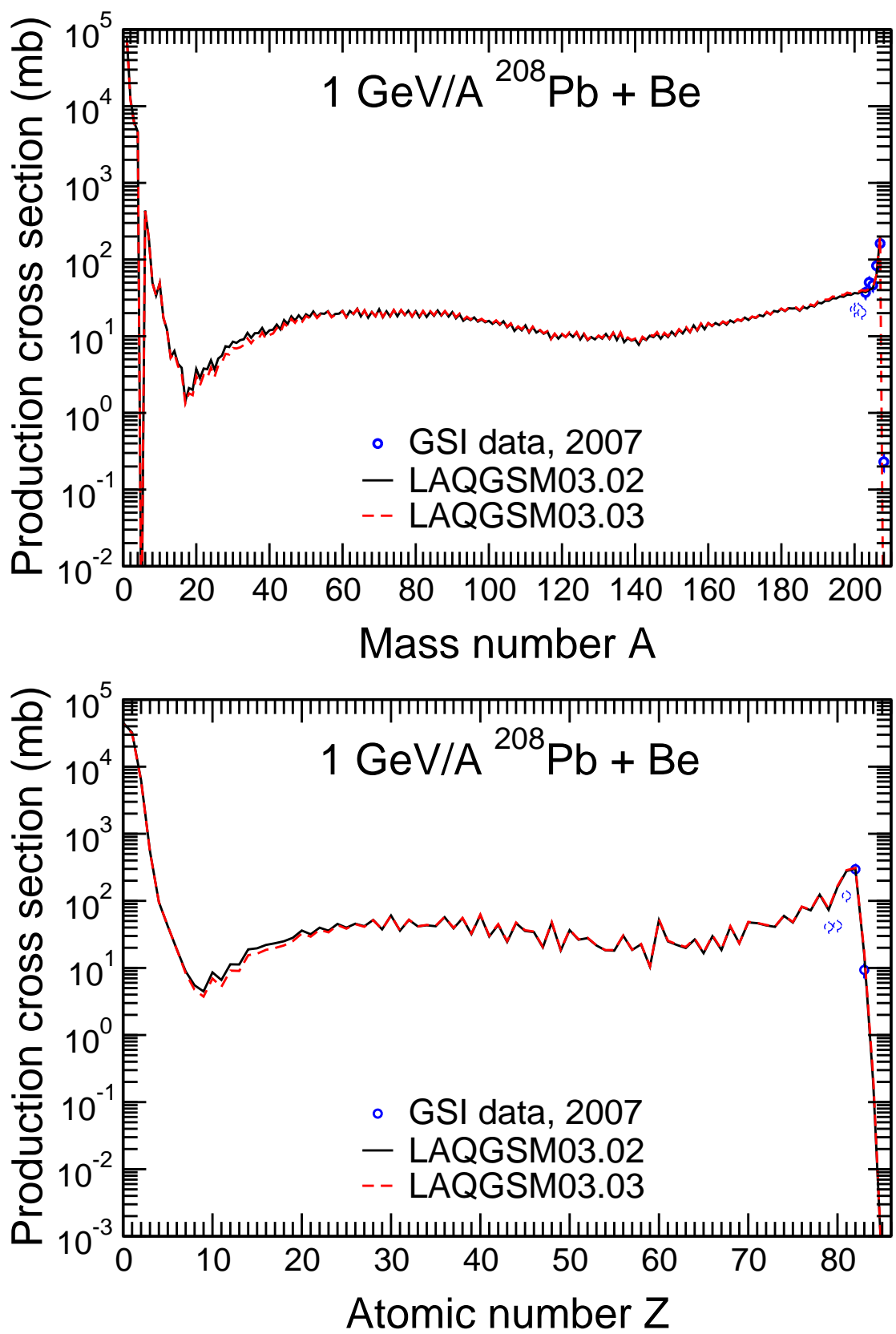


Figure 4: Mass- and charge-number distributions of the yield of all products from the reaction $1 \text{ GeV/nucleon } ^{208}\text{Pb} + ^9\text{Be}$. Symbols are GSI measurements of Nieto *et al.* [39]; dashed lines are results from LAQGSM03.03, while solid lines are results from LAQGSM03.02 [12].

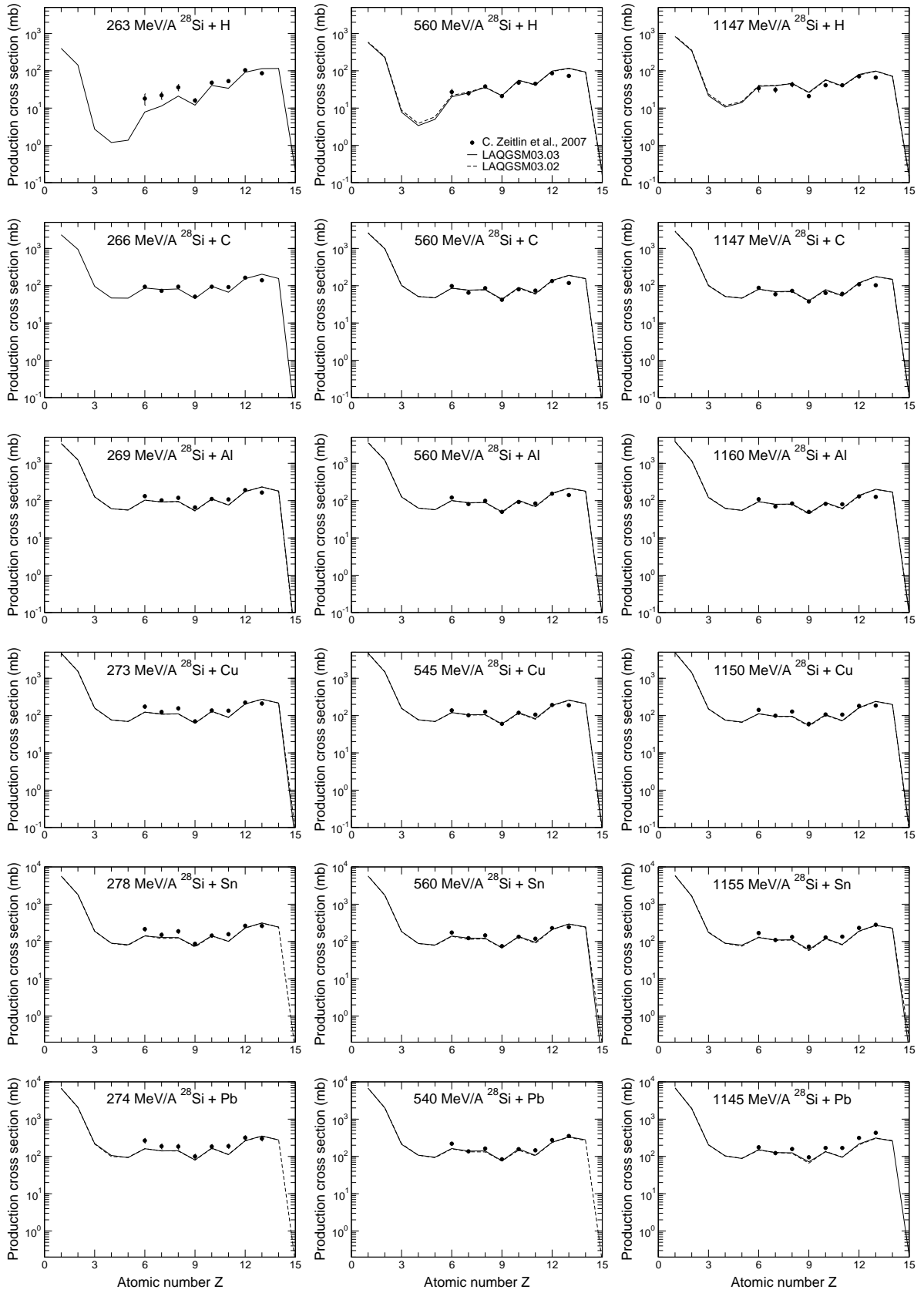


Figure 5: Atomic-number dependence of the fragment-production cross sections from the interactions of ^{28}Si of about 270, 560, and 1150 MeV/nucleon with H, C, Al, Cu, Sn, and Pb, as indicated. Filled circles are measurements by Zeitlin *et al.* [40]; solid lines are results from LAQGSM03.03, while dashed lines are results from LAQGSM03.02 [12].

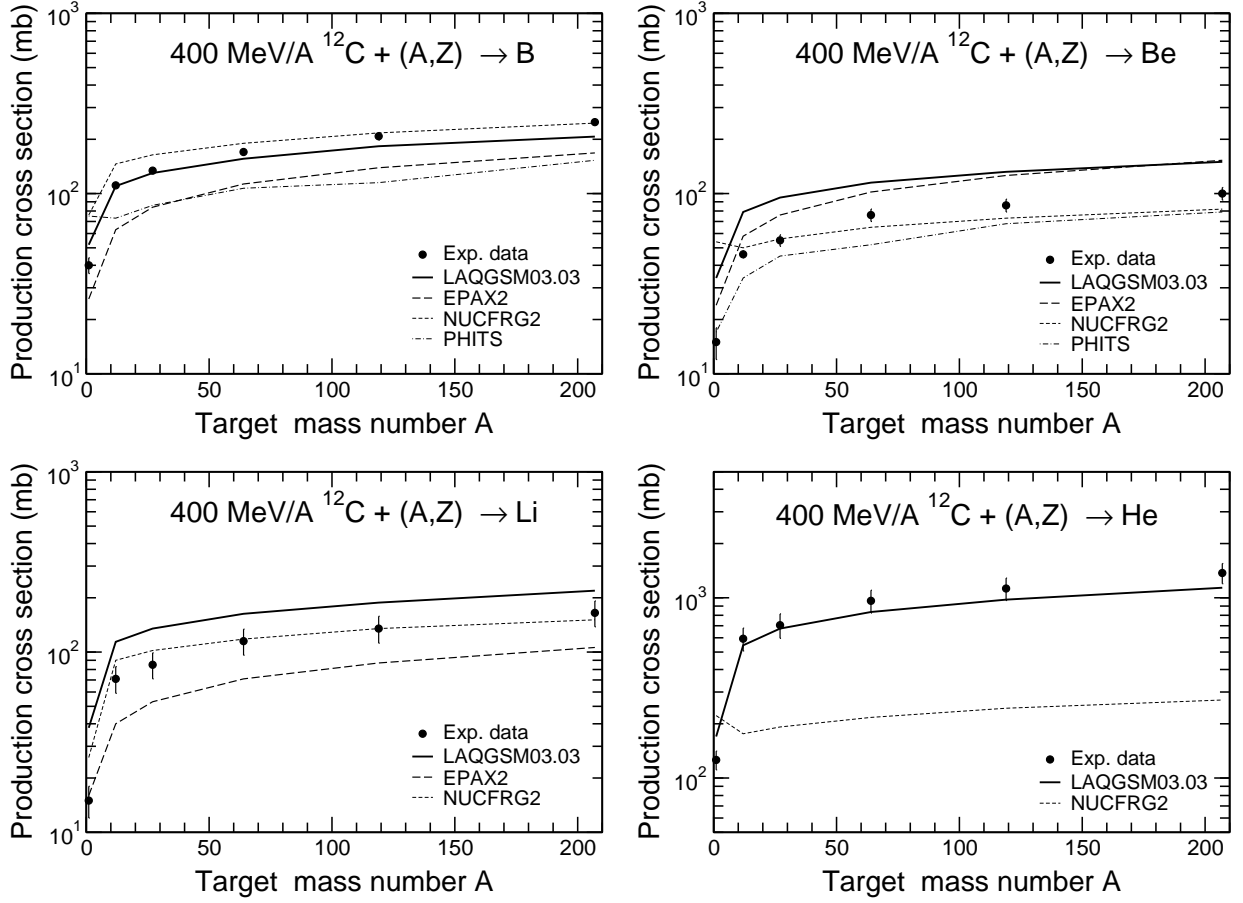


Figure 6: Target mass-number dependence of B, Be, Li, and He production cross sections from the interactions of 400 MeV/nucleon ^{12}C with H, C, Al, Cu, Sn, and Pb. Filled circles are measurements by Zeitlin *et al.* [41]; Solid lines are results from LAQGSM03.03 compared with experimental data and with results from EPAX2 [42], NUCFRG2 [43], and PHITS [44] taken from Tab. VII of Ref. [41].

Fig. 6 and 7 show recent data from two more experiments performed at HIMAC by the same group of Zeitlin *et al.*, namely, B, Be, Li, and He yields from interactions of ^{12}C with H, C, Al, Cu, Sn, and Pb at 400 and 290 MeV/nucleon, respectively [41]. These data are of interest for cancer therapy with carbon ions used currently at several facilities, as well as for radiation protection of astronauts on long-duration space missions (see references and details in [41]). This is why the authors of the measurements have analyzed their data with widely used phenomenological systematics EPAX2 [42], the one-dimensional NASA transport code NUCFRG2 [43], and with the recent Japanese transport code PHITS [44]; for comparison, results from these codes taken from Tabs. IV and VII of Ref. [41] are also shown in Figs. 6 and 7 together with our LAQGSM03.03 results.

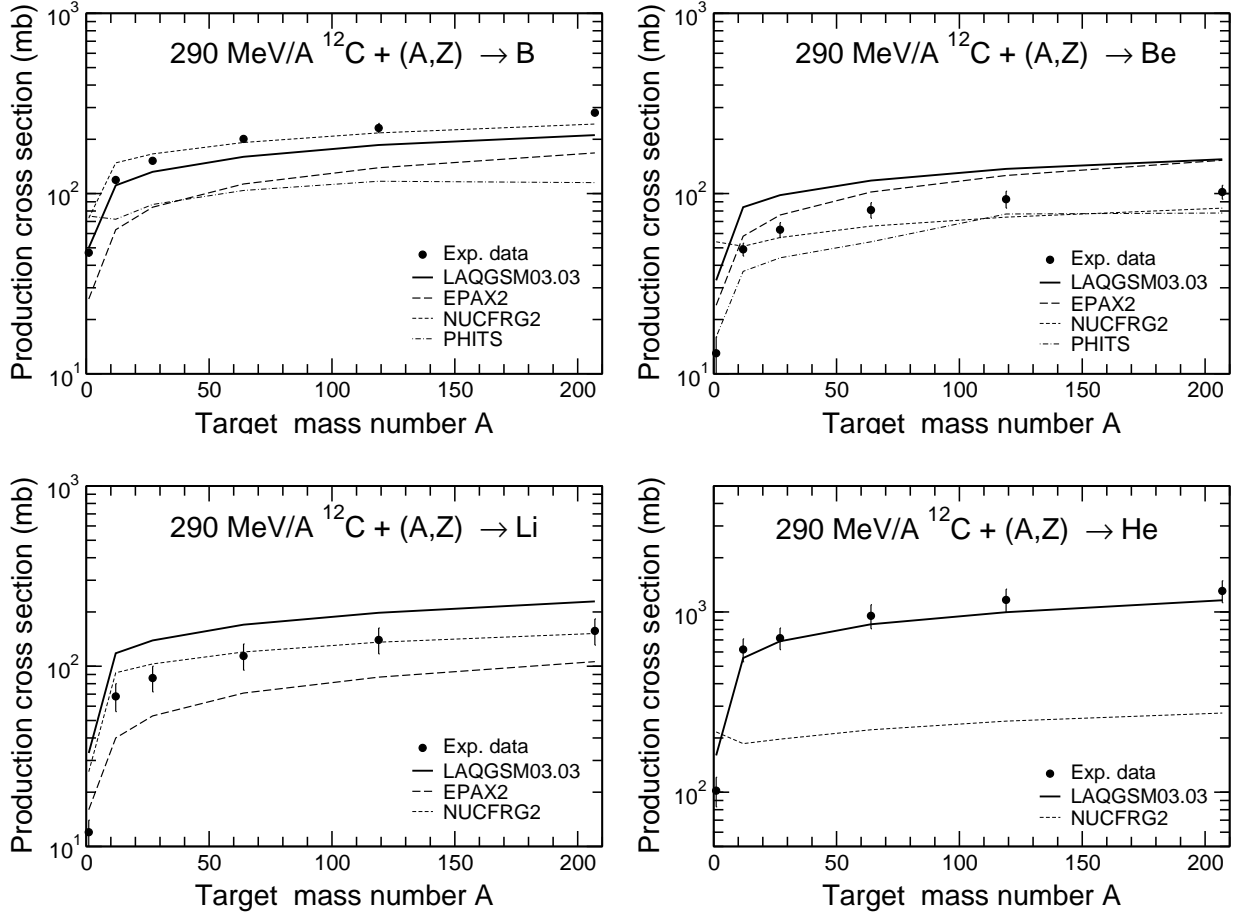


Figure 7: Target mass-number dependence of B, Be, Li, and He production cross sections from interactions of 290 MeV/nucleon ^{12}C with H, C, Al, Cu, Sn, and Pb. Filled circles are measurements by Zeitlin *et al.* [41]. Solid lines are results from LAQGSM03.03 compared with experimental data and with results from EPAX2 [42], NUCFRG2 [43], and PHITS [44] taken from Tab. IV of Ref. [41].

The extracted experimental charge-changing cross sections [41] shown in Figs. 6 and 7 were obtained at three distinct values of angular acceptance, and can not be compared directly with results of calculations by LAQGSM03.03 or by other models that do not account for the real complexity of the experiment (see details in [41]). However, we see a reasonable agreement of our results with these experimental data and with results by other codes, though a straightforward comparison of calculations with these data is difficult. On the whole, LAQGSM03.03 agrees with these measurements no worse than EPAX2 [42], NUCFRG2 [43], and PHITS [44], and does especially well for He production.

Fig. 8 shows one more set of data measured at Brookhaven National Laboratory by the same group; namely, fragmentation cross sections for ^{56}Fe on H, C, Al, Cu, and Pb targets at 1.05 GeV/nucleon [45], compared with measurements of the same reactions at nearby energies of 1.88 GeV/nucleon by Westfall *et al.* [46], 1.55 GeV/nucleon by Cummings *et al.* [47], and 1.086 GeV/nucleon by Webber *et al.* [48], as well as with LAQGSM03.03 results. LAQGSM03.03 describes these data very well.

Fig. 9 shows a test of LAQGSM03.03 on another type of data: inclusive pion production spectra in proton-beryllium collisions at 6.4, 12.3, and 17.5 GeV/c obtained from data taken by the already quite old E910 measurement at Brookhaven National Laboratory, but analyzed and published only a month ago [49]. LAQGSM03.03 describes these pion spectra quite well, just as we obtained with previous versions of LAQGSM for other spectra of different ejectiles measured by the E910 experiment.

Finally, Figs. 10–19 show a comparison of our results with the recent extensive measurements by Mocko *et al.* of the projectile fragmentation of ^{40}Ca , ^{48}Ca , ^{58}Ni , and ^{64}Ni at 140 MeV/nucleon on ^9Be and ^{181}Ta targets measured at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University [50, 51] and of fragmentation of ^{86}Kr at 64 MeV/nucleon on the same targets, measured at RIKEN [51, 52]. These measurements are similar in their technique to experiments done recently at GSI at higher energies, analyzed with previous versions of LAQGSM [6]–[12]; one example is shown in Figs. 3 and 4. The cross sections for the production of different isotopes of different elements obtained in this type of measurement are much more informative and useful for applications, as well as in developing and testing nuclear-reaction models than are the charge-changing integral cross sections [40, 41], [45]–[48] discussed above. It is much more difficult to describe with a model such detailed cross sections than to describe integral yields of products, or spectra of emitted particles; this is why such data are extremely useful to validate models and codes. In fact, Dr. Mocko has analyzed [51] these measurements with the empirical parameterization EPAX [42], with the more detailed but still semi-phenomenological Abrasion-Ablation (AA) model [53] as implemented into the LISE++ code [54] and the Heavy-Ion Phase-Space Exploration (HIPSE) model [55], as well as with the more complicated Antisymmetrized Molecular Dynamics (AMD) model [56]. Dr. Mocko has found [51] that none of these models in their standard versions are able to describe well the whole set of data [50, 52], and all of them would need to be improved to agree with these measurements. Figs. 10–19 show that LAQGSM03.03 agrees quite well with the whole set of measured cross sections, especially considering that these calculations are done with a fixed model, without changing or fitting anything. In fact, these calculations were done before having numerical values of the experimental data. We received from Dr. Mocko a list of reactions to be calculated, performed our calculations and sent him the results. He then compared our results with the measurements and plotted Figs. 10 to 19 (as well as others, to be published in a future common paper on this analysis). From Figs. 10 to 19 we see that the agreement of our results with the data [50, 52] is good but not perfect, there is room for future improvements of LAQGSM. But even in its current “03.03” version, LAQGSM describes the data better than do any other models or phenomenological parameterizations so far considered (see details in [51]).

Acknowledgment

We are grateful to Drs. Arnold Sierk, Mircea Baznat, Michal Mocko, and Paolo Napolitani for useful discussions. This work was carried out under the auspices of the U. S. Department of Energy (DOE) and National Aeronautics and Space Administration (NASA).

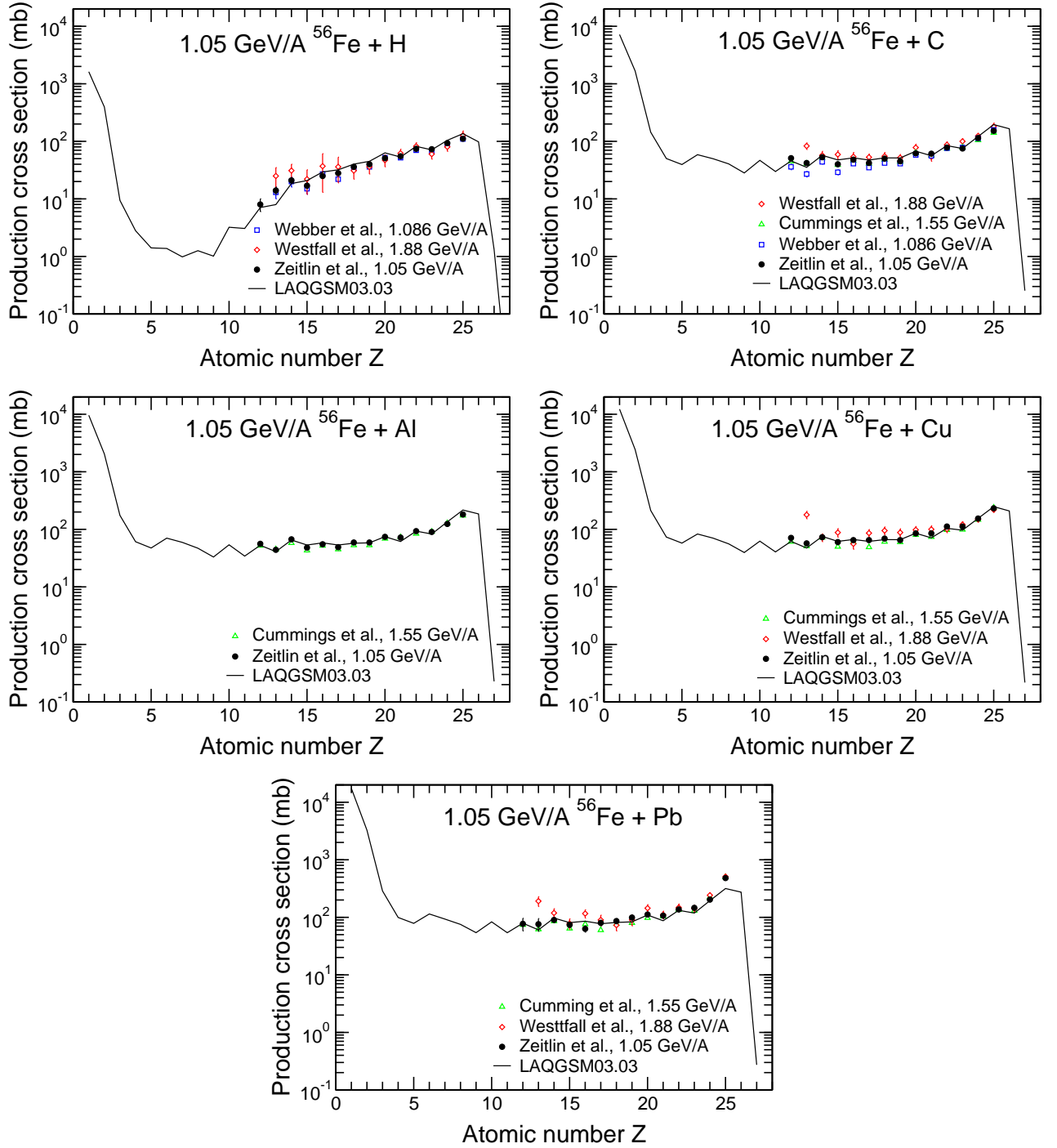


Figure 8: Atomic-number dependence of the fragment production cross sections from interactions of 1.05 GeV/nucleon ^{56}Fe with H, C, Al, Cu, and Pb. Filled circles show the measurements by Zeitlin *et al.* [45]; solid lines are results from LAQGSM03.03. For comparison, measurements of the same reactions at nearby energies of 1.88 GeV/nucleon by Westfall *et al.* [46], 1.55 GeV/nucleon by Cummings *et al.* [47], and 1.086 GeV/nucleon by Webber *et al.* [48], are shown with colored diamonds, triangles, and squares, respectively.

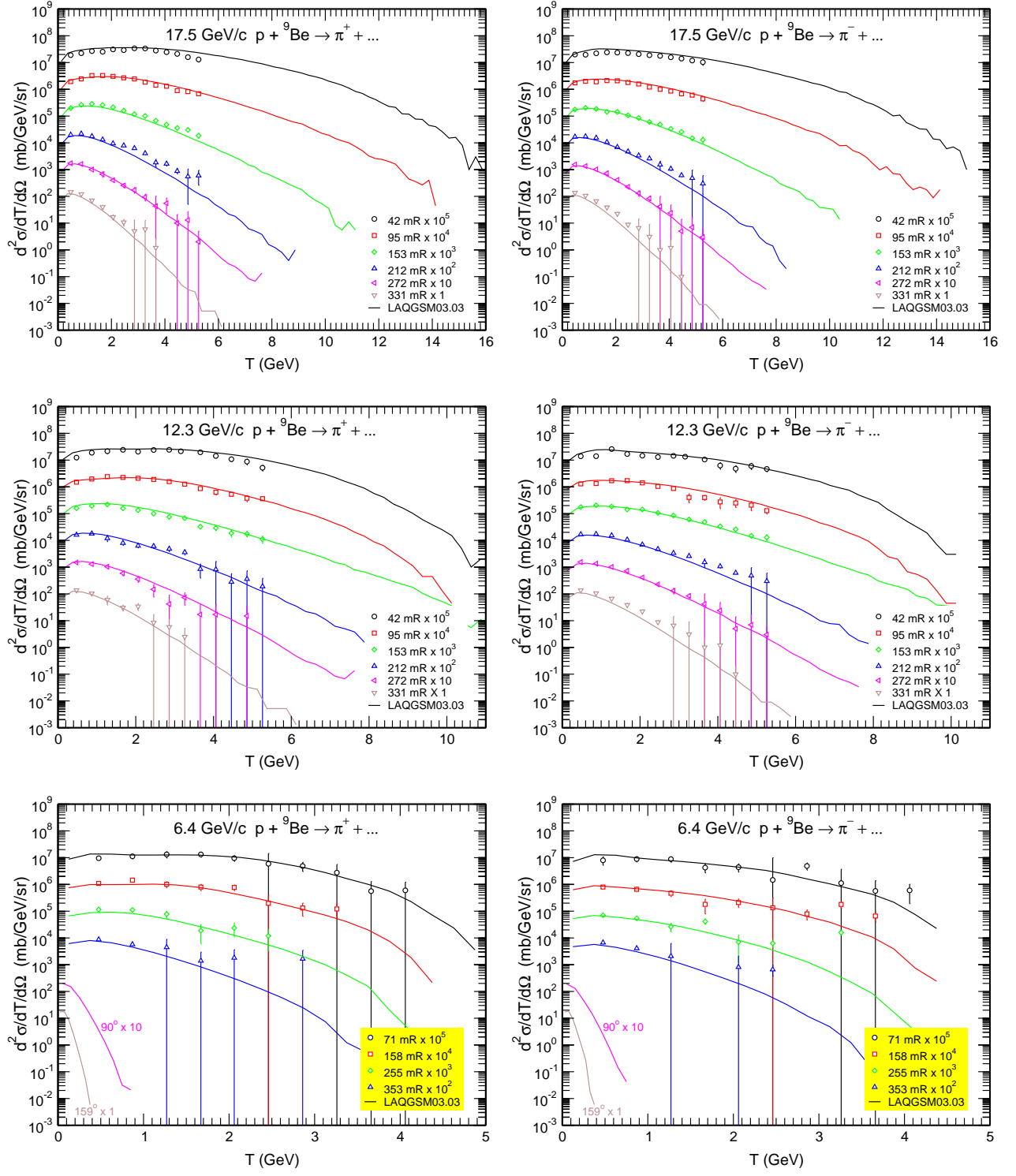


Figure 9: Measured inclusive forward π^+ and π^- spectra from 6.4, 12.3, and 17.5 GeV/c $p + {}^9\text{Be}$ [49] compared with LAQGSM03.03 results at angles of detection as indicated in the plots. For reactions induced by 6.4 GeV/c protons, we also show LAQGSM03.03 predictions for unmeasured spectra at 90 and 159 degrees.

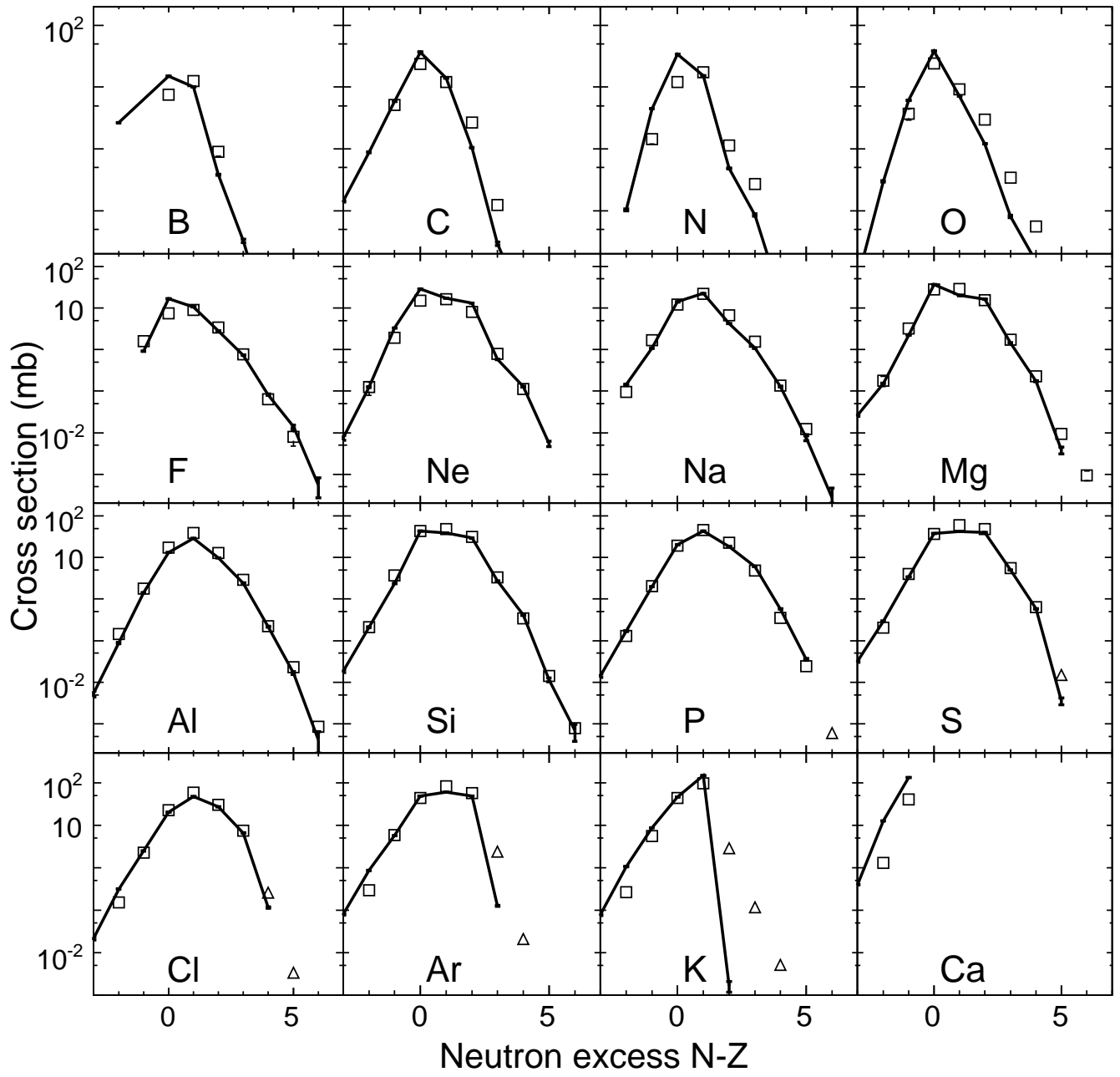


Figure 10: Measured cross sections for ^{40}Ca fragmentation on ^9Be at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

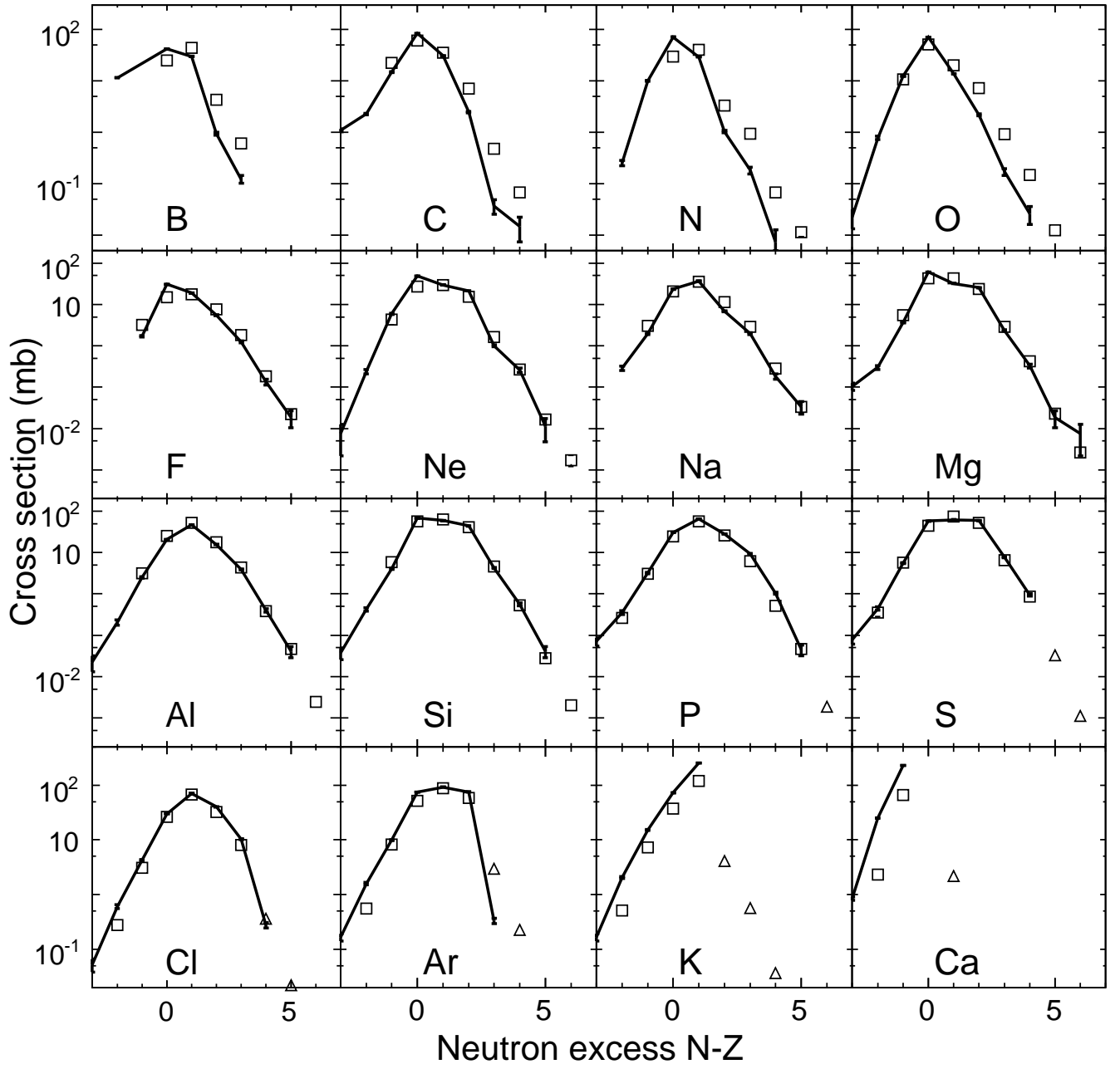


Figure 11: Measured cross sections for ^{40}Ca fragmentation on ^{181}Ta at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

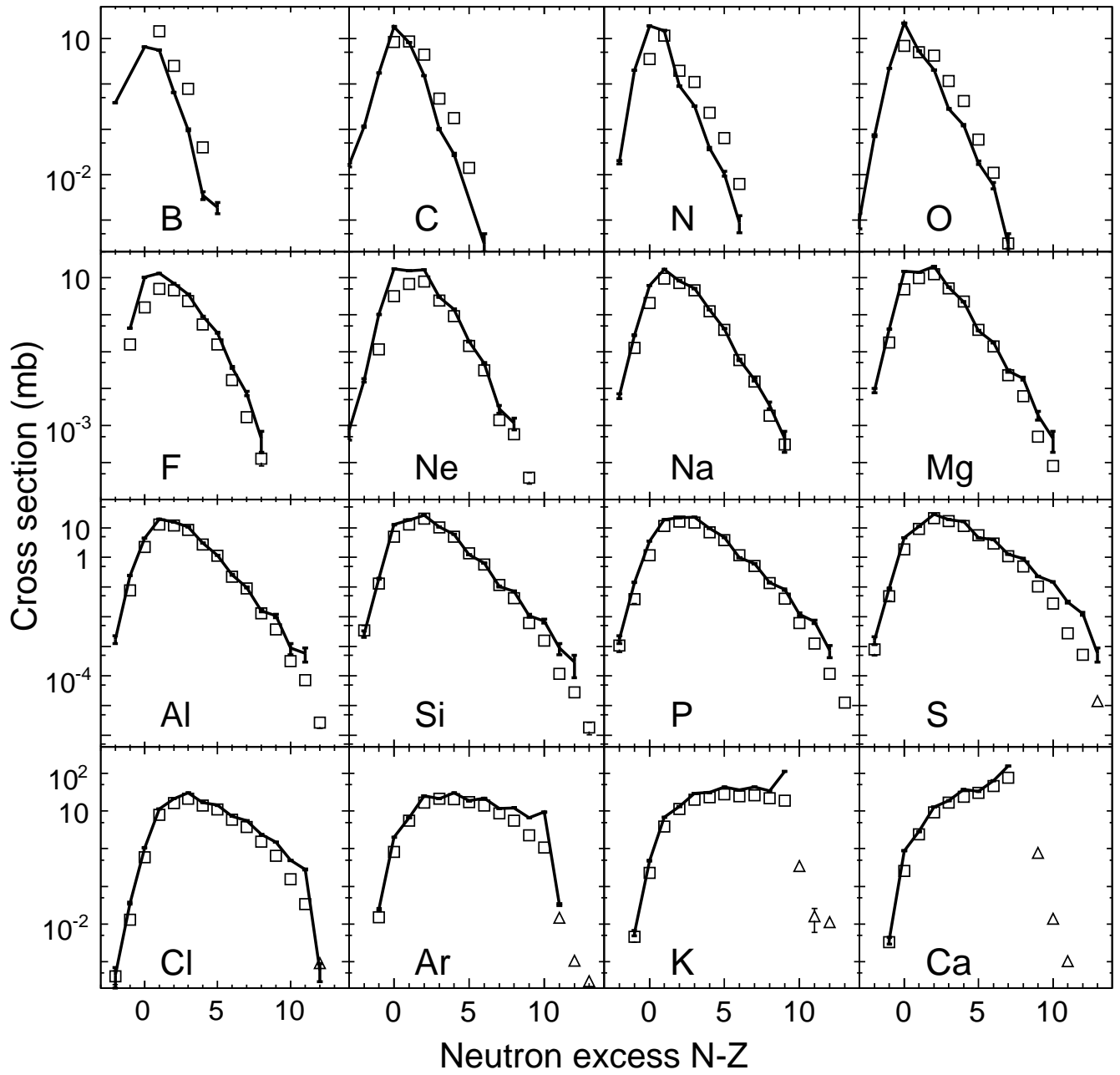


Figure 12: Measured cross sections for ^{48}Ca fragmentation on ^9Be at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

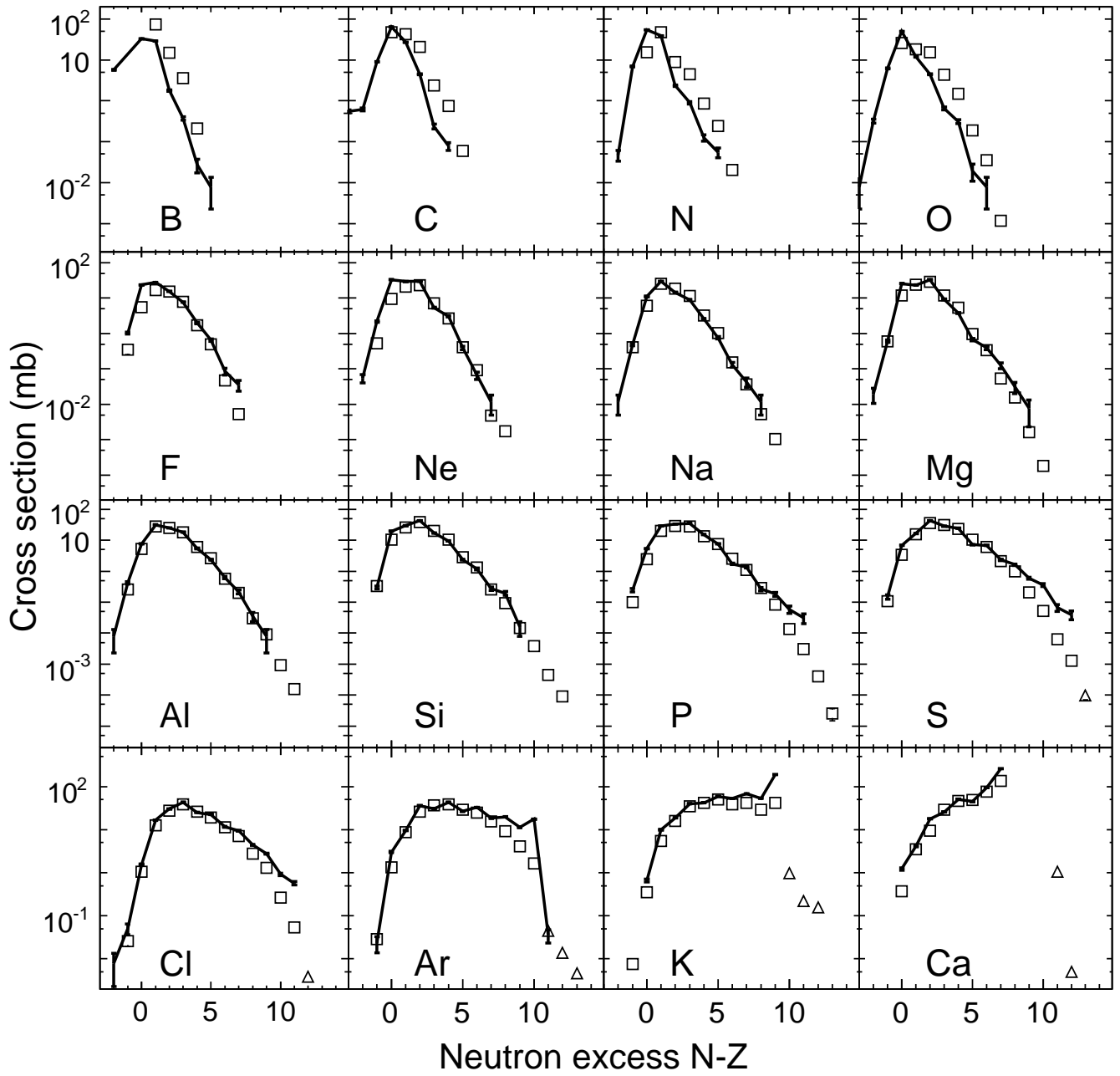


Figure 13: Measured cross sections for ^{48}Ca fragmentation on ^{181}Ta at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

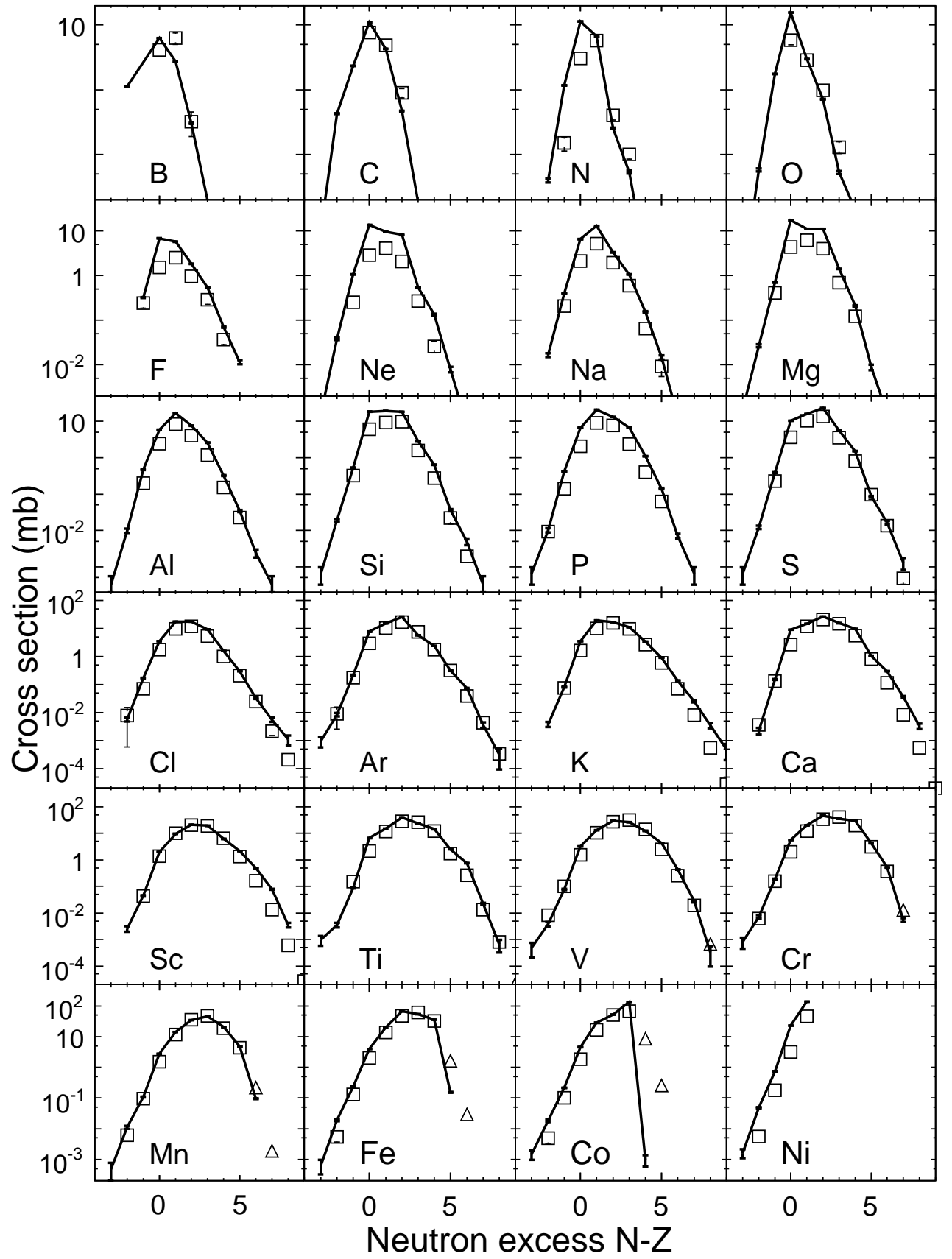


Figure 14: Measured cross sections for ^{58}Ni fragmentation on ^9Be at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

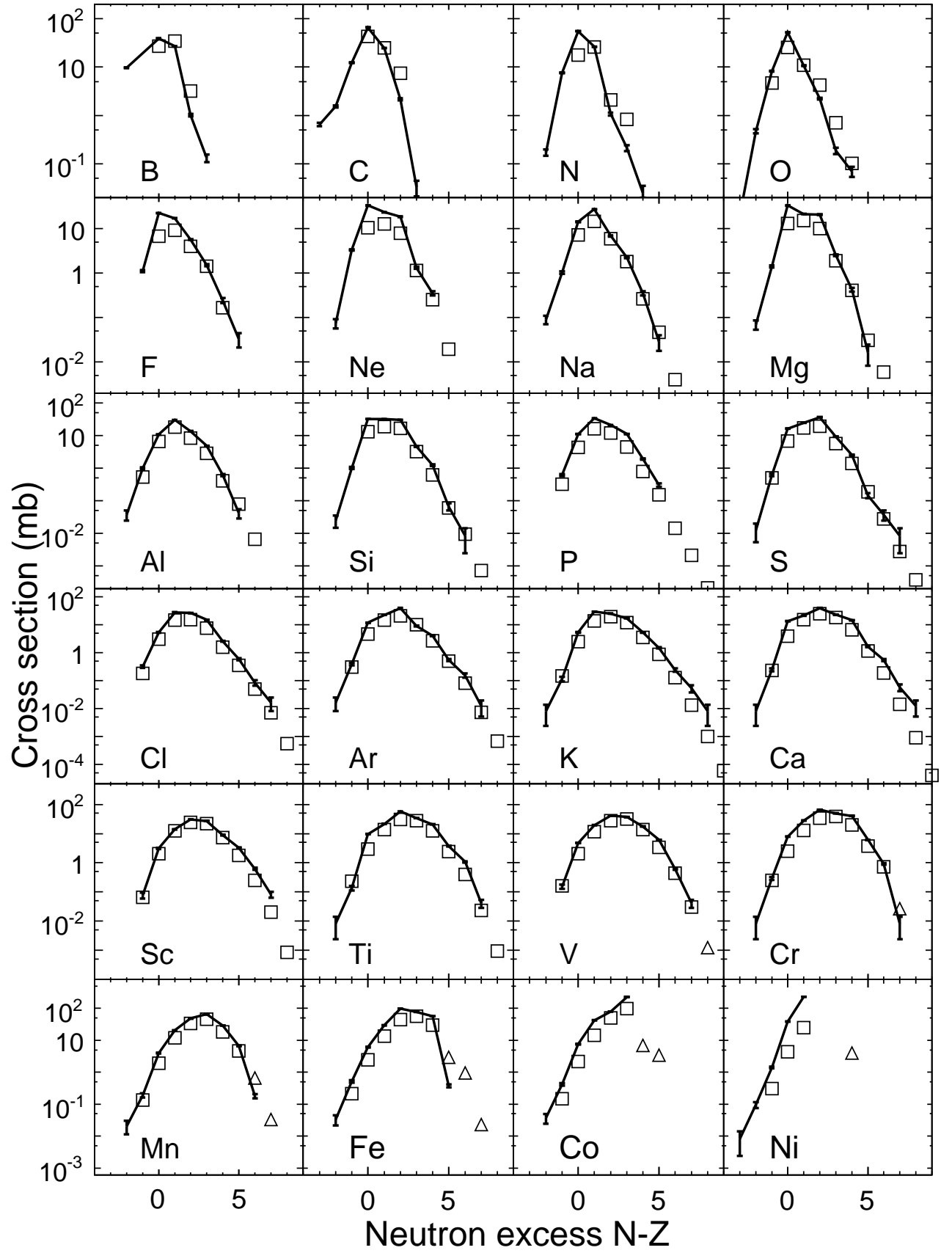


Figure 15: Measured cross sections for ^{58}Ni fragmentation on ^{181}Ta at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

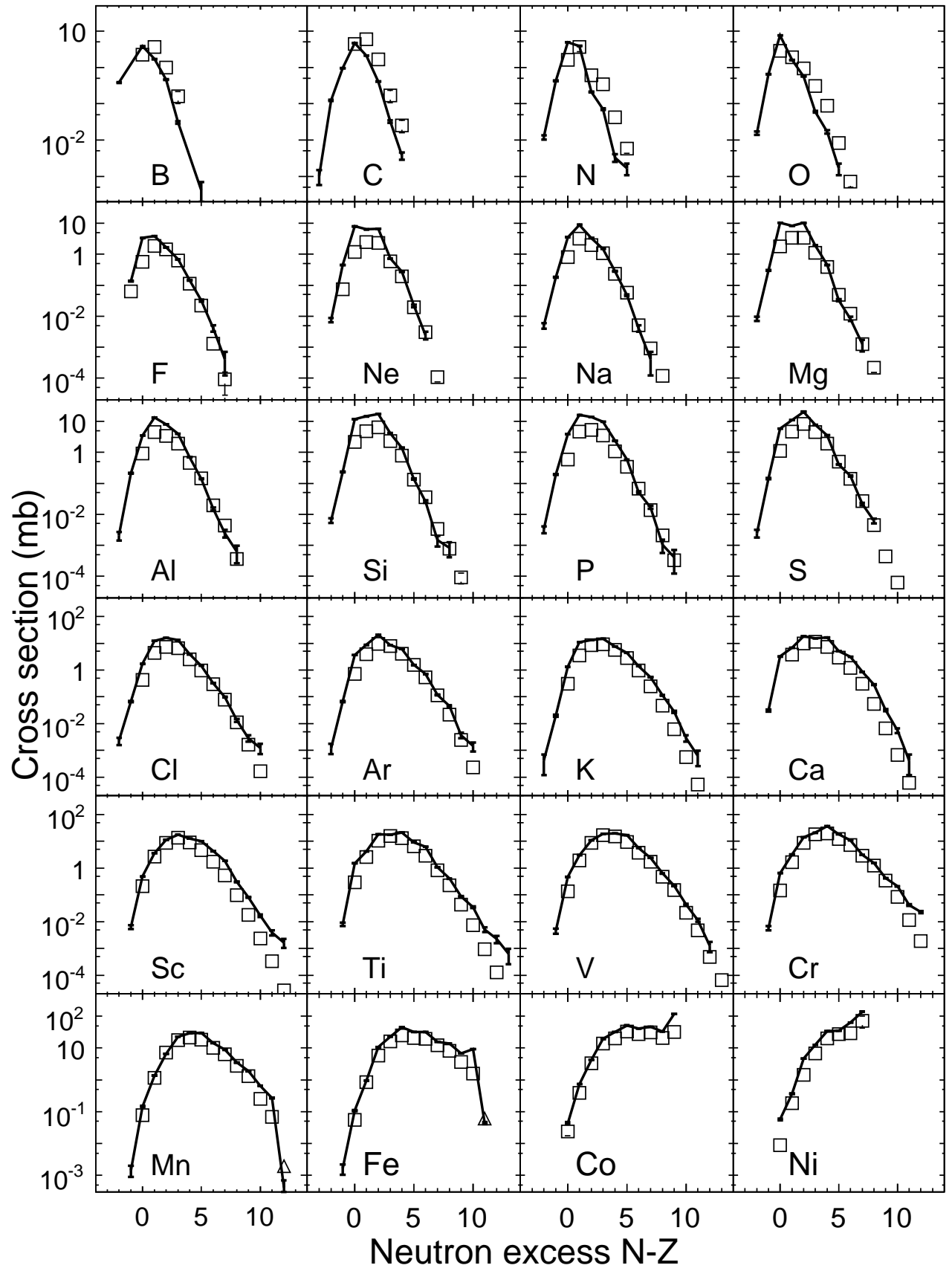


Figure 16: Measured cross sections for ^{64}Ni fragmentation on ^9Be at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

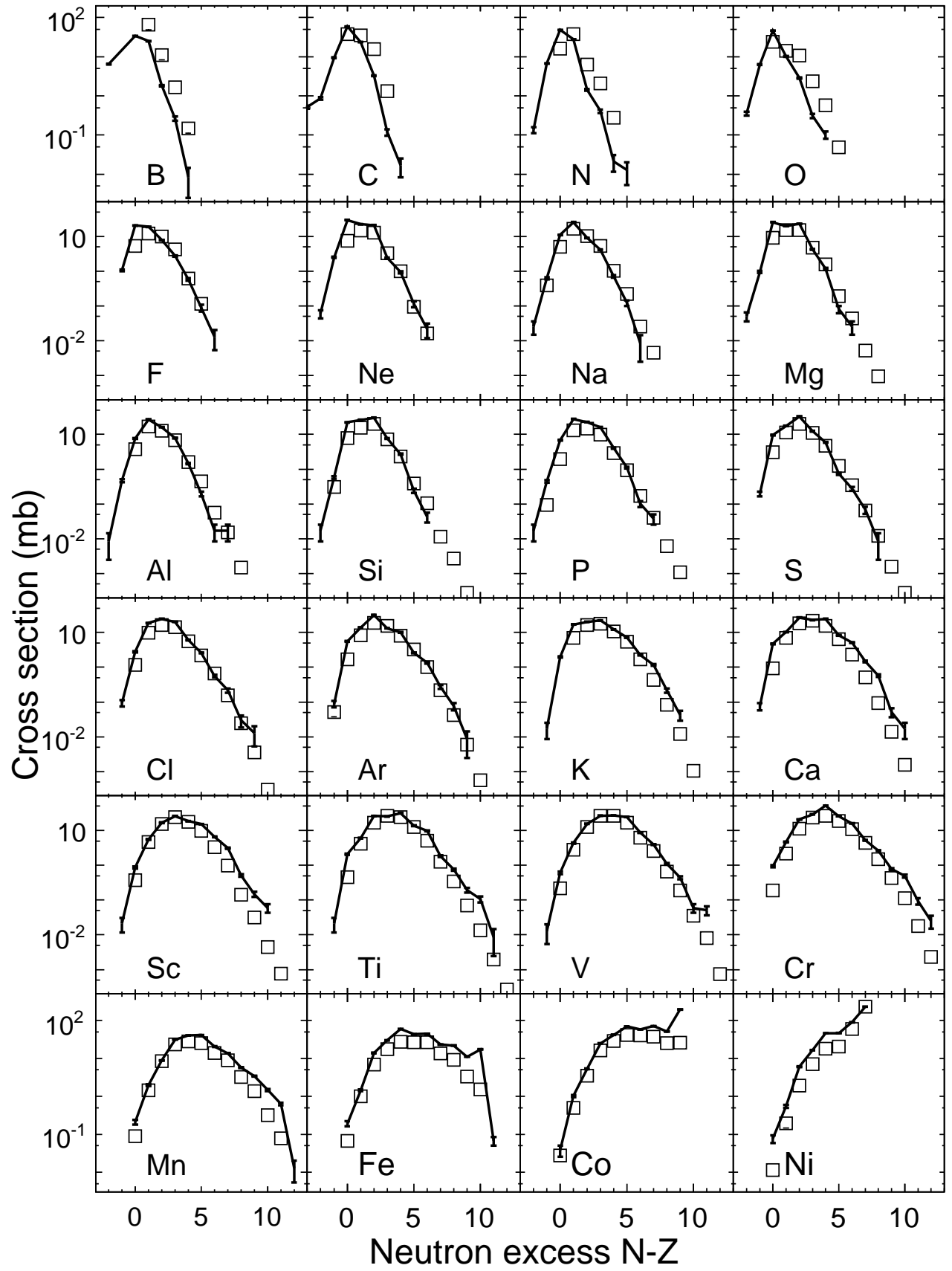


Figure 17: Measured cross sections for ^{64}Ni fragmentation on ^{181}Ta at 140 MeV/nucleon [50, 51] compared with LAQGSM03.03 predictions.

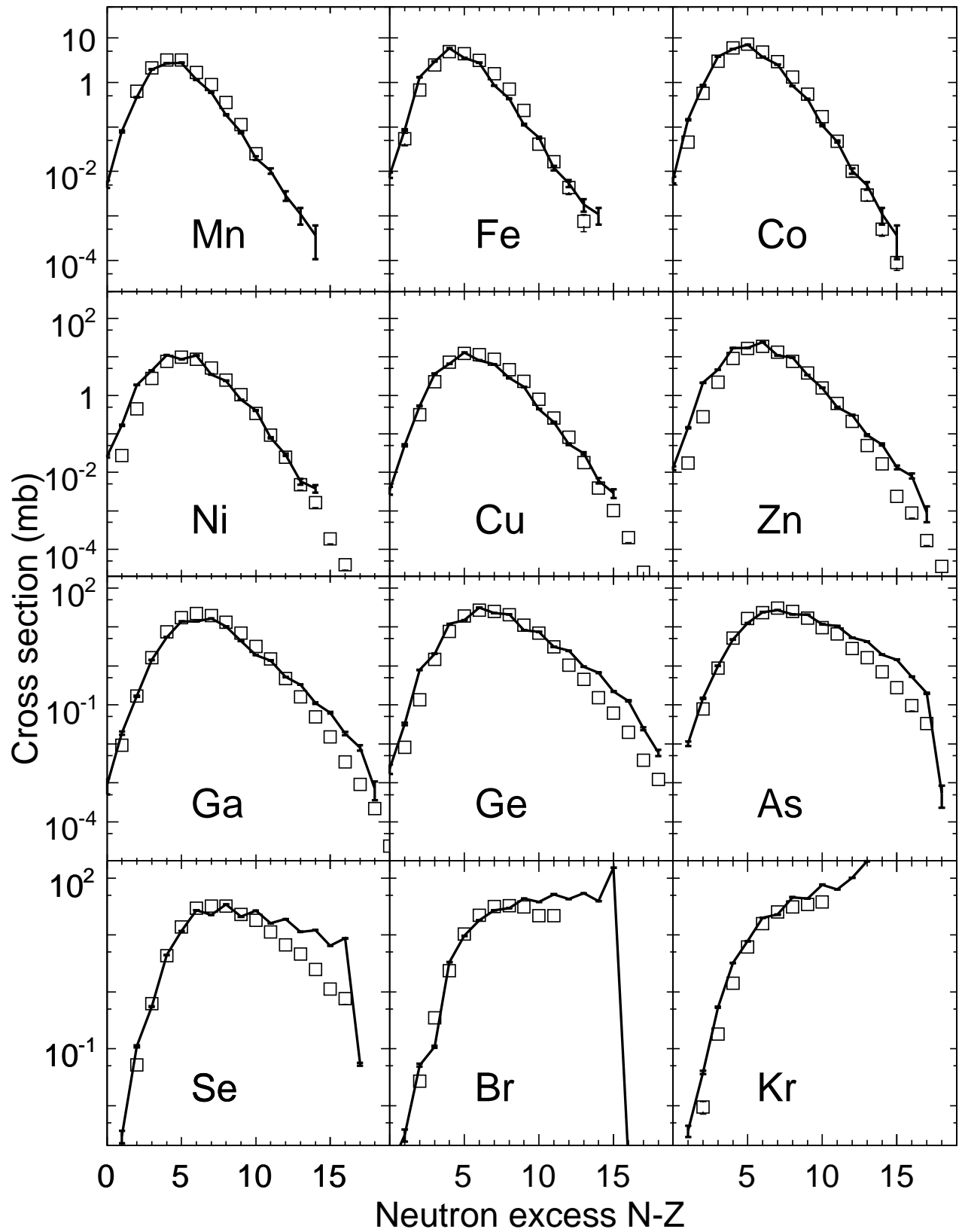


Figure 18: Measured cross sections for ^{86}Kr fragmentation on ^9Be at 64 MeV/nucleon [51, 52] compared with LAQGSM03.03 predictions.

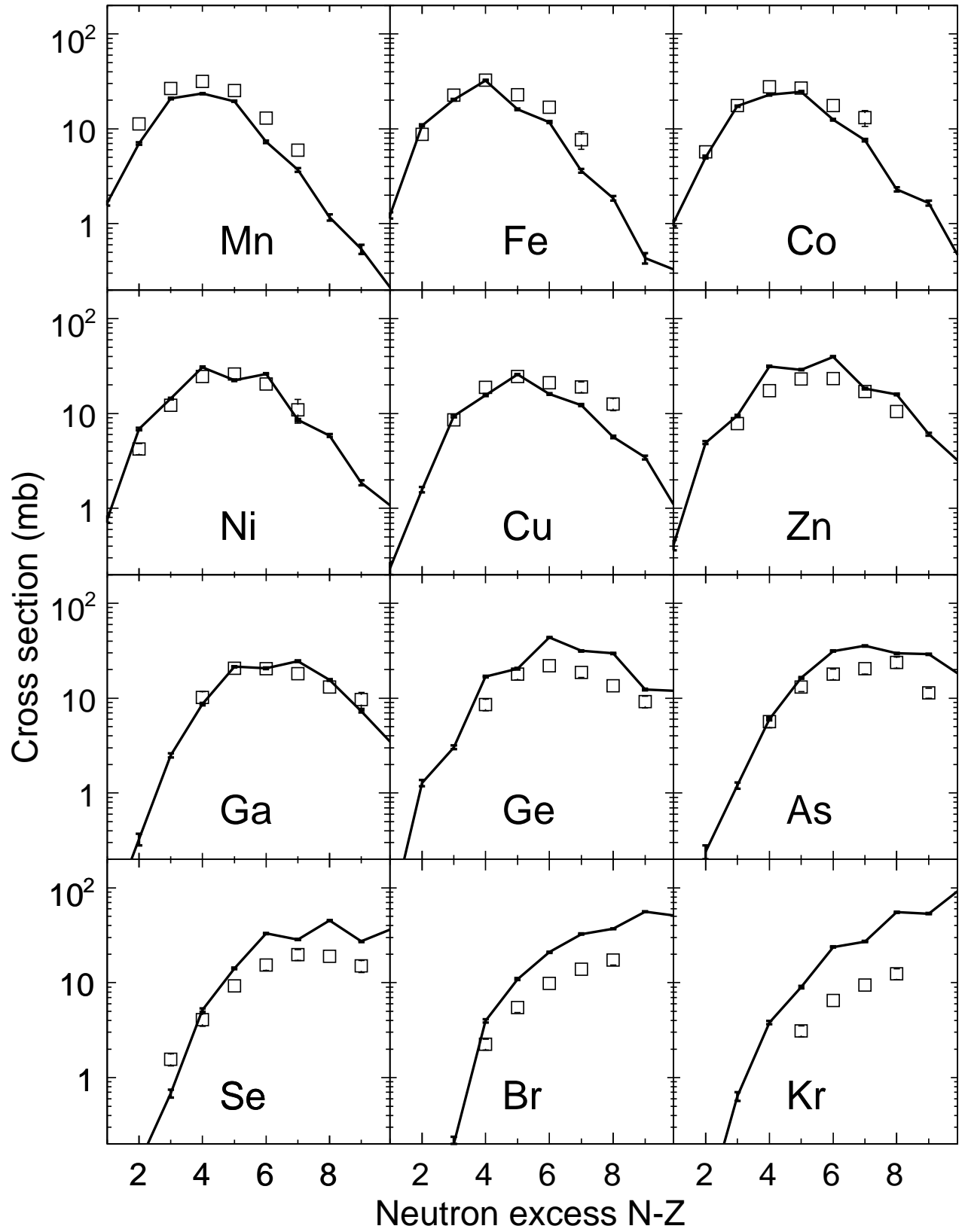


Figure 19: Measured cross sections for ^{86}Kr fragmentation on ^{181}Ta at 64 MeV/nucleon [51, 52] compared with LAQGSM03.03 predictions.

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